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博士論文の要約

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Spectroscopic Study of Correlated Electron-Hole Systems in Silicon Nanostructures

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Abstract

A significant improvement in Si-based nanofabrication techniques has opened opportunities to investigate the interacting electron-hole systems in low dimensional systems such as Si nanolayers and Si nanowires. Under high optical excitation density and at low carrier temperature, free exciton gas or electron-hole plasma (EHP) is known to condensate to the liquid phase called electron-hole droplet (EHD). There have been continuous efforts to clarify theoretical aspects of the interacting electron-hole systems. The correlation energy increases by the confinement of carriers to lower dimensional structures and this favors for transition to the EHD phase. The confinement, however, also induces lifting of the degeneracy of otherwise six-fold degenerate conduction band minima in bulk Si, and reduces the binding energy of the EHD phases and thus reduces the transition temperature to EHD phase T_c. It is, therefore, not obvious whether the confinement of carriers favors for transition to the EHD phase. Although the carrier condensation in low dimensional systems has been recognized as a fundamental problem of many-body physics, extensive experimental investigations for the phase diagrams of carriers in low dimensional systems have not been available yet. The main purpose of this research is to reveal the stability and the mechanism of carrier condensations in low dimensional systems. In this thesis, extensive results of photoluminescence (PL) measurements of Si nanostructure, namely, Si nanolayers and Si nanowires (NWs) are presented.

Si nanolayers were fabricated by thermal oxidation of a (100)-oriented silicon-on-insulator (SOI) wafer obtained from SOITEC Company. The thickness of the nanolayer samples was varied between 2.7 and 25.2 nm. Si nanowire samples were fabricated by thermal oxidation of Si fin structures defined by photolithography followed by a reactive ion etching. PL was measured with a continuous wave laser at the wavelength of 325 nm and detected by a liquid-nitrogen cooled InGaAs multichannel detector using a micro-PL setup. The PL decay profiles were measured using a single-photon counting technique with a pulse laser at the wavelength of 325 nm and repetition frequency of 200 kHz at low temperatures between 4 and 70 K.

The thickness dependence of integrated PL intensity from Si nanolayer at the lattice temperature between

6 and 24 K was investigated. The integrated PL intensity normalized by the absorption in the nanolayer was found to increase with decrease in the nanolayer thickness. The reduction of layer thickness dependence of integrated PL intensity with the increase in the lattice temperature was attributed to increase in diffusion coefficient.

The temperature dependencies of the equilibrium carrier density of EHD are investigated from the optical excitation density and lattice temperature dependence of PL spectra of Si nanolayers. The line shape of the broad PL band is given by the product of the convolution of the electron and the hole populations. The broadening of PL spectra is introduced by the product of the convolution of the PL line shape and the Gaussian distribution. The numerical fits of the broad PL band provide the amplitude of the PL spectra, the carrier temperature, the Fermi energy, or two dimensional carrier density, the band-gap energy and the broadening of PL spectra. The width of the broad PL was found to increase with decrease in the layer thickness. The experimentally obtained carrier density, the Fermi energy and the chemical potential were fit to a quadratic function of the carrier temperature obtained from the minimization of the free energy of the EHL. The smaller carrier density dependence on the carrier temperature for the thinner nanolayer samples was found. This has been explained by the transition from three-dimensional density of states to quasi-two-dimensional density of states by the vertical confinement of the conduction band electrons.

The phase boundary between EHD and EHP are obtained. It has been found that the observed maximum transition temperature T_c between EHP and EHD increase with decrease in the layer thickness. It has been found that the PL lifetime decreases with decrease in the thickness of nanolayers between 25.2 and 2.7 nm and that the PL lifetime depends significantly on the temperature.

The spatial mappings of PL from Si nanowire samples reveal small spatial variations of the PL peak energy and the amplitude, showing that Si NWs are formed with excellent uniformity over a large area. While the carrier temperatures of $T_e = 17 – 27$ K were estimated from the broad PL band at the low energy side of the exciton peak at high optical excitation condition, a clear evidence for the increase of T_c due to the confinement in the Si nanowire samples has not been obtained. The annealing temperature dependence of PL peak intensities of Si NWs has been investigated and it has been found that the PL peak intensity is maximized at 400 ^{o}C for each NW type. The obtained results are consistent with previous reports on the transport measurements of similar structures. Therefore, the obtained results show that the technique of micro-PL measurement mentioned above is useful as a nondestructive method of characterizing Si nanostructures like NW reported here.

In this research, the PL from electron-hole systems in silicon nanostructures has been investigated. The analysis of the PL properties has clarified the correlation effect in silicon nanostructured and revealed that the EHD in quasi-two dimensional silicon exist at the carrier temperature above the critical temperature of EHD in bulk silicon.